Mitigating Methane in Jordan: National Inventory, Emission Projections, and Policy Pathways

Alham Al-Shurafat: Department of Environmental Engineering, North Carolina State University (NCSU), USA
Fayez Abdulla: Department of Civil Engineering, Jordan University of Science and Technology (JUST), Jordan
Ayman Sharafat: Climate Action Network Jordan (CAN), Amman, Jordan

ABSTRACT

BACKGROUND: Jordan lacks a comprehensive national methane inventory integrating multi-sectoral sources, projections, and policy pathways. Despite methane's outsized climate impact (28× CO_2e over 100 years) and contribution to health-harming ozone, existing local studies focus narrowly on waste sector point sources, neglecting agriculture (19% of emissions) and energy (10%). This gap impedes evidence-based integration of methane mitigation into climate and health policies.
OBJECTIVE: This study establishes Jordan's first national methane inventory, projects emissions to 2050, quantifies sector-specific mitigation potentials, and evaluates policy pathways for inclusion in revised climate commitments.
METHODS: Using the Low Emissions Analysis Platform–Integrated Benefits Calculator (LEAP-IBC), we quantified 2022 baseline emissions across energy, transport, agriculture, and solid waste/wastewater sectors and projected trends to 2050 based on population and GDP growth. Data were sourced from national ministries (2019–2023), with IPCC emission factors applied. Stakeholder-validated mitigation measures were modeled under three scenarios (short- [2022–2029], mid- [2030–2040], long-term [2041–2050]) against a business-as-usual (BAU) projection. Methane impacts were converted to CO_2e using $GWP_{100} = 28$.
RESULTS: Baseline emissions (2022) totaled 6,978.9 Gg CO_2e/a, dominated by solid waste/wastewater (70%, 4,886.2 Gg), followed by agriculture (18.8%, 1,308.7 Gg) and energy (10.3%, 720.2 Gg). Under BAU, emissions rise 86% by 2050 (~13,000 Gg CO_2e/a), driven by population growth (11.3M→19M) and extreme urbanization (91.8% urban). Mitigation scenarios achieve 39.3% reduction by 2030 and 51.3% by 2050. The waste sector offers the highest cumulative reduction (4,600.8 Gg CO_2e/a by 2050 via landfill gas capture and biogas), followed by energy (1,389.3 Gg CO_2e/a via renewables and efficiency). Jordan's methane profile is distinct—waste emissions exceed global averages due to urbanization and refugee pressures.

Key words

Methane, Jordan, LEAP-IBC, CH_4 inventory, Mitigation Potential

1. Introduction

Methane (CH_4) is a powerful greenhouse gas, the atmospheric amount of which has more than doubled since pre-industrial times (Nisbet et al. 2019). It has been second only to carbon dioxide (CO_2) in driving climate change during the industrial era. Methane is a short-lived climate pollutant (SLCP). SLCPs—encompassing black carbon, methane, hydrofluorocarbons (HFCs), and tropospheric ozone (O_3) alongside its precursors (Carbon Monoxide (CO), Non-Methane Volatile Organic Compounds (NMVOCs), and Nitrogen Oxides (NO_x))—exhibit atmospheric lifetimes ranging from days to slightly over a decade(Climate & Clean Air Coalition, n.d.). Despite their transient nature, SLCPs contribute approximately one-third of current global warming (World Economic Forum 2024) and are linked to severe health risks and environmental degradation. Rapid mitigation of black carbon and methane alone could curb projected warming by up to 0.5°C by 2050, avert 2.4 million annual premature deaths, and prevent 52 million tons of crop losses by 2030 (Hussein et al. 2019).

Methane atmospheric lifetime of roughly a decade (the perturbation lifetime, relevant for dealing with emission reductions, is 12 years). Methane contributes to the formation of tropospheric ozone (O_3), which, like methane, is a short-lived but powerful greenhouse gas and tropospheric ozone is also an air pollutant with detrimental effects on people, ecosystems and crops. Emissions of methane into the atmosphere are therefore harmful to society in multiple ways. While methane is not directly dangerous to human health, it does indirectly affect it and agricultural productivity through ozone and climate change. Recent studies have found evidence of these consequences to health and agricultural damage (D. Shindell and Smith 2019) to be larger than previously believed. These new studies include the finding that tropospheric ozone may have much higher impacts on public health, particularly respiratory and cardiovascular deaths (Turner et al. 2016). In addition, understanding of methane's effect on radiative forcing has recently improved, leading to an upward revision since the Fifth Intergovernmental Panel on Climate Change (IPCC) Assessment (D. T. Shindell, Fuglestvedt, and Collins 2017; Etminan et al. 2016). Taken together, improved understanding suggests that the overall societal impact of methane emissions is likely larger than indicated by prior estimates. In large part, because of its impacts on public health and agriculture, the broad social cost of methane, that is the monetized societal damage, including climate and air quality related impacts, resulting from a tonne of emissions is 50–100 times greater, depending on the preferred discount rate (D. T. Shindell, Fuglestvedt, and Collins 2017), than the corresponding social cost of carbon dioxide, before taking into account the recent updates.

Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5°C. Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45%, or 180 million tonnes a year by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts. It would also, each year, prevent 255,000 premature deaths, 775 000 asthma related hospital visits, 73 billion hours of lost labor from extreme heat, and 26 million tonnes of crop losses globally. More than half of global methane emissions stem from human activities in three sectors: fossil fuels (35% of human-caused emissions), waste (20%) and agriculture (40%). In the fossil fuel sector, oil and gas extraction, processing and distribution account for 23 per cent, and coal mining account for 12% of emissions. In the waste sector, landfills and wastewater make up about 20% of global anthropogenic emissions. In the agricultural sector, livestock emissions from manure and enteric fermentation represent roughly 32%, and rice cultivation 8% of global anthropogenic emissions (UNEP 2021).

Existing research on methane in Jordan exhibits a pronounced focus on individual emission sources or specific sites, with the solid waste sector receiving predominant attention. Studies such as (Alrbai et al. 2022), optimizing Landfill Gas recovery at Al Ghabawi landfill, and (Z. Al-Ghazawi and zboon 2021), assessing Irbid's composting plant, exemplify this site-specific approach, quantifying local efficiency gains or emission avoidance but lacking national extrapolation. Similarly, research on Al-Akaider landfill (al Ajlouni 2022), composting in Al-Karak (Al-Nawaiseh et al. 2021), or fruit and vegetable waste potential in Amman markets (Papirio et al. 2022) remained confined to single facilities or waste streams. Even broader analyses, like (H. Abu-Qdais, Al-Ghazawi, and Awawdeh 2022) assessment of 18 landfills or (Myyas et al. 2023) review of national biomass potential, were fundamentally anchored within the waste management sector (Al-Zoubi, Alkhamis, and Alzoubi 2024).

While offering valuable insights into waste-related methane—such as scenario comparisons demonstrating composting's mitigation efficacy (H. Abu-Qdais et al. 2019) or early projections for wastewater and landfill emissions (Qteishat et al. 2024; AlQaraleh, Hajar, and Matarneh 2024; Z. Al-Ghazawi and Abdulla 2008)—these studies share a critical limitation. They primarily address isolated components of Jordan's methane profile. Consequently, a significant gap persists: the absence of a comprehensive, multi-sectoral national methane inventory integrating projections and mitigation pathways across all key sources, including agriculture and energy, beyond the well-studied waste domain.

Therefore, this study presents a comprehensive methane inventory for Jordan, bridging a critical data void that has hindered evidence-based climate and health policies. By leveraging advanced energy and non-energy resources modeling, we project methane emissions and reduction potentials from 2022 to 2050 across its sources sectors. Four scenarios are evaluated: a baseline scenario reflecting current policies was established based on the baseline year 2022, alongside three mitigation scenarios extracted from the national plans, policies, commitments, projects, and strategies— short-term, covering the ongoing until 2029; mid-term, spanning 2030 to 2040; and long-term, extending from 2041 to 2050—that outline the implementation of climate change mitigation interventions planned for future pursuit by local authorities.

This work is quantified sector-specific reduction potential, providing policymakers with tools to align national strategies with global SLCPs mitigation goals. This initiative is part of Jordan's ongoing national project *"Jordan – Deliver Policy Analysis and Recommendations on SLCP Mitigation"*("Jordan - Deliver Policy Analysis and Recommendations on SLCP Mitigation [JO-22-001] | Climate & Clean Air Coalition," n.d.) funded by Climate and Clean Air Coalition (CCAC) to assist Jordan Ministry of Environment at advancing mitigation measures to reduce SLCPs and ultimately integrating these measures into Jordan's revised Nationally Determined Contributions (NDCs).

2. Methodology and data

2.1 Overview

This study employs a systematic approach to quantify Jordan's methane emissions, project future trends, and evaluate the mitigation potential of climate change mitigation planned national policies. The methodology integrates data collection, stakeholder engagement, and advanced modeling using the Low Emissions Analysis Platform–Integrated Benefits Calculator (LEAP-IBC)("LEAP: Low Emissions Analysis Platform," n.d.) at the sectoral level.

2.2 Data Collection and Baseline Inventory

2.2.1 Emission Data: Data acquisition was conducted through direct correspondence with Jordan's pertinent authorities and ministries through an official request from Jordan Ministry of Environment within a national level collaboration for the project "Jordan – Deliver Policy Analysis and Recommendations on SLCP Mitigation"("Jordan - Deliver Policy Analysis and Recommendations on SLCP Mitigation [JO-22-001] | Climate & Clean Air Coalition," n.d.) which aims to support Jordan's Ministry of Environment in identifying priority SLCP mitigation measures to be included in Jordan's revised NDCs. Data spanning the five years was obtained (2019 – 2023).

2.2.2 Supporting Data: Socio-economic drivers, including population growth and GDP growth, were sourced from Department of Statistics (DOS), and Jordan's National Communication Reports under the UNFCCC (UNDP 2022).

2.2.3 Emission Factors

Default methane emission factors from the IPCC(Eggleston et al. 2006) Guidelines were applied across energy and agricultural sectors. These internationally standardized factors provide a consistent baseline for national greenhouse gas inventories. Table 1 summarizes the IPCC-derived methane emission factors used for key sources in Jordan's inventory.

Table 1: Summary of Methane Emission Factors from Energy and Agricultural Sources

Category	Source/Fuel/Animal	CH_4 Emission Factor	Unit
Energy & Transportation	Oil	126.9	kg CH_4 / TJ
	Natural Gas	42.5	kg CH_4 / TJ
	Coal	24.0	kg CH_4 / TJ
	Diesel	414.0	kg CH_4 / TJ
	Gasoline	127.5	kg CH_4 / TJ
	Liquid Petrolum Gas (LPG)	44.8	kg CH_4 / TJ
	Kerosene	42.0	kg CH_4 / TJ
	Jet Fuel	42.0	kg CH_4 / TJ
Agriculture	Buffalo (Manure)	5.0	kg CH_4 / animal / year
	Buffalo (Enteric)	55.0	kg CH_4 / animal / year
	Sheep (Manure)	0.2	kg CH_4 / animal / year

	Sheep (Enteric)	0.2	kg CH_4 / animal / year
	Goats (Manure)	0.2	kg CH_4 / animal / year
	Goats (Enteric)	5.0	kg CH_4 / animal / year
	Camels (Manure)	2.2	kg CH_4 / animal / year
	Camels (Enteric)	18.0	kg CH_4 / animal / year
	Poultry (Manure)	0.02	kg CH_4 / animal / year
	Poultry (Enteric)	0.0	kg CH_4 / animal / year

2.3 Sectoral Data Inventory

Jordan's population in 2022 was 11.26 million, with 7.7 million Jordanians and 3.3 million non-Jordanians, including 1.3 million Syrians refugees. The population is highly urbanized, with 42% living in the capital Amman and only 9.7% living in rural areas. It is projected to grow to 19 million by 2050, doubling every 29 years, with 2 million households averaging 4.8 persons. Urbanization has risen from 59.9% in 1980 to about 91.83% in 2022 ("Jordan Urban Population 1960-2025 | MacroTrends," n.d.) with rural areas consuming more water due to agricultural activities. Rapid population growth, urbanization, and refugee influxes are straining food, water, and infrastructure demands(UNDP 2022). Here are the national current circumstances of the sectors that emit methane:

2.3.1 Solid Waste

Since 2020, Jordan produces more than 3 million tons of Municipal Solid Waste (MSW) yearly—0.6 kg per person daily in rural areas and 0.9 kg in urban areas, half of which is organic (Ministry of Environment 2020). About 50% of Jordan's waste goes to the engineered Al-Ghabawi landfill, while the rest ends up in unsafe sites, risking health and the environment. Informal recycling handles under 10% of waste (Hajar et al. 2020). The sector accounts for 10.6% of total GHGs emissions, 98.6% resulting from methane from landfills (The World Bank 2022)

The Ministry of Local Administration (MOLA) is responsible for solid waste management across Jordan, excluding the capital city of Amman as handled by the Greater Amman Municipality (GAM), and supervises all local municipalities, with minimal involvement from the private sector.

Therefore, solid waste data was collected from both MOLA and GAM (See Table 2).

Table 2: Municipal Solid Waste Data for Jordan (2019-2023)

Items	Quantity for 2019 (tons/a)	Quantity for 2020 (tons/a)	Quantity for 2021 (tons/a)	Quantity for 2022 (tons/a)	Quantity for 2023 (tons/a)
Solid waste of MOLA	1,662,939	1,795,410	2,649,479	2,914,427	1,732,412.5
Solid waste of GAM	1,456,074	137,4835	1,350,539	1,368,886	1,406,023
TOTAL	3,119,013	3,170,245	4,000,018	4,283,313	3,138,436

2.3.2 Wastewater

Jordan has 23 wastewater treatment plants (WWTPs) to treat wastewater for reuse, that could reduce agriculture's freshwater demand. The government seeks new technologies in several areas, including recycling sludge; and improved energy efficiency at treatment facilities (Qteishat et al. 2024). WWTPs provide service to about 68% of the population while the others use septic tanks. The total inflow to WWTPs is 300,000 m^3/d, of which about 250,000 m^3/d inflows to As-Samra WWTP (Al-Zboon et al. 2008). Jordanian standards allow discharging treated wastewater to streams and for restricted agriculture either near the plants or downstream after mixing with natural surface water (Qteishat et al. 2024). WWTPs produce 100% dried sewage sludge. Most sludges are either stored onsite or dumped in landfills, contaminating groundwater and emitting significant methane during decomposition (Internationale Zusammenarbeit (GIZ) 2023). Data (Table 3) for this sector were collected from Jordan's Ministry of Water and Irrigation (MWI), which represents the primary stakeholder for this sector.

Table 3: Wastewater Treated and Sludge Produced for Jordan.

Items	Quantity for 2019	Quantity for 2020	Quantity for 2021	Quantity for 2022
Quantities of sludge produced from sewage plants (tons/year)	105,125	108,278	111,527	114,872
Quantities of Wastewater treated (Million m^3 (MCM)/year)	186	187	196	215

2.3.3 Agriculture

As of 2018 agriculture's contribution to the total national gross domestic product (GDP) was about 5.6%, and accounts for about 16% of the total export . Jordan's agricultural sector produced about 1.15 million tons (MT) of carbon dioxide equivalent (CO_2eq) in 2017 and the forestry sector reported 0.87 MT CO_2 eq emissions in 2014 because of soil organic carbon loss in the rangelands. This is closely linked with unsustainable livestock practices, including overgrazing and consequent land degradation (The World Bank 2022). Jordan's agricultural sector, particularly livestock production, significantly contributes to methane emissions through enteric fermentation and manure management. The Jordanian Ministry of Agriculture (MoA) serves as the primary stakeholder for this sector. According to MoA, livestock population trends from 2019–2022 by animal type (in thousand heads) are shown in Table 4.

Table 4: Livestock Population Trends in Jordan (2019–2022) by Animal Type (Thousand Heads)

Animal Type	Quantities (one thousand heads) 2019	Quantities (one thousand heads) 2020	Quantities (one thousand heads) 2021	Quantities (one thousand heads) 2022
Poultry	1961	1565	1977	1530
Lamb	3107.2	3503.5	3162.7	3513
Goat	3973	4430.8	3940.7	4354
Cows	92.600	91.500	93.250	91.500
Camels	10.87	10.8	11	11

2.3.4 Energy & Transport

Jordan's energy sector relies heavily on imported fossil fuels (92% of primary energy)(Dar-Mousa and Makhamreh 2019. With annual energy demand rising by 3% (Abu-Rumman, Khdair, and Khdair 2020), Jordan aims to diversify its mix via renewables (14% by 2030) (Ababneh et al. 2023; UNDP, n.d.), nuclear plans ("Nuclear Power in Jordan - World Nuclear Association," n.d.), while targeting a 10% emissions reduction by 2030 (UNDP, n.d.). However, the rapidly growing building sector (4–5% annually) (Nazer 2019) lacks robust decarbonization strategies (Alasmar, Schwartz, and Burman 2024).

Jordan's energy and transport sectors contribute to methane emissions primarily through fugitive releases during natural gas extraction, transmission, and distribution, as well as incomplete fuel combustion in vehicles, power plants, and aviation. For this study, energy and transport-related data were collected from official sources, including the Ministry of Energy and Mineral Resources

(MEMR) and the Ministry of Transport for fuel production and consumption, the Land Transport Regulatory Commission (LTRC) for road vehicle numbers and types, and the Civil Aviation Regulatory Commission (CARC) for aviation fuel use, with detailed figures consolidated in Table 5.

Table 5: Fuel Consumption in Jordan (2022) - By Sector - in Thousand Tons of Oil Equivalent

Fuel Type	Energy Sector (Excl. Transportation)	Transportation Sector
Oil	1,803.0	-
Natural Gas	224.4	-
Coal	225.8	-
Diesel	508.2	1,151.6
LPG	599.3	-
Kerosene	72.5	-
Biomass	36.5	-
Gasoline	-	1,459.8
Jet Fuel	-	307.7
Fuel Oil	-	4.2
Grand Total	**3,470.2**	**2,923.3**

2.4 Modeling Framework

The LEAP-IBC model was used to estimate methane emissions, project future trends, and assess mitigation potential. LEAP-IBC integrates energy demand, non-energy activities, emission factors, and socio-economic drivers to simulate emissions under different scenarios (Kuylenstierna et al. 2020). Key steps included:

2.4.1 Baseline Emissions

For the assessment of the methane for Jordan in the solid waste, wastewater, agriculture, energy and transport Sectors, the baseline year has been set to 2022 since it was the year with the most updated sufficient and reliable data available from the relevant ministries and authorities. Additionally, it reflects the most recent representative situation following the COVID-19 pandemic, as 2020 and 2021 do not accurately represent the business-as-usual scenario.

2.4.2 Methane Emissions Calculations and Factors

All methane emission calculations follow LEAP-IBC's integrated modeling framework(“LEAP: Low Emissions Analysis Platform,” n.d.), with sector-specific formulas and parameters extracted directly from the model. Key equations and factors applied include:

A. For the energy and transportation sectors, methane emissions were calculated using the formula:

$$E = \sum_j \sum_k C_{jk} EF_{jk}$$

Where E is total methane emissions, Cjk is fuel consumption, and EFjk is the emission factor for fuel type j in sector k.

B. Landfill methane emissions were calculated using the formula:

$$\textbf{Methane Emissions } (\mathbf{CH_4}) = \text{MSW\_decomposed} \times \text{DOC} \times \text{DOCf} \times \text{F} \times (12/16) \times (1 - \text{Oxidation Factor}) \times \text{MCF}$$

Where: MSW_decomposed = Mass of decomposable Municipal Solid Waste (MSW) (Gg/year), was obtained directly form the MoLA and GAM as shown in Table 2; DOC = Degradable Organic Carbon (fraction of MSW that can decompose) (~0.5); DOCf = Fraction of DOC that actually decomposes (typically ~0.5); 16/12 = Molecular weight conversion (CH_4 vs. C); Oxidation Factor = Fraction of CH_4 oxidized by landfill cover (default ~0.1); MCF = Methane Correction Factor (accounts for anaerobic conditions, used 0.6 which is within the range of (0.4–1.0).

Note that we estimated Jordan's landfill waste has a degradable organic carbon (DOC) content of 0.25 (0.5*0.5), higher than the Mediterranean average (0.18–0.22) and within IPCC's range for developing nations (0.14–0.28). This elevated value indicates greater methane generation potential.

C. Methane emissions from wastewater are calculated using a modified version of the previous IPCC equation (Eggleston et al. 2006):

$$\mathbf{CH_4} \textbf{ Emissions (Gg/year)} = \text{TOW} \times \text{DOC} \times \text{DOCf} \times \text{MCF} \times \text{F} \times (16/12) - \text{R}$$

Where TOW – Total Organic Wastewater (kg BOD/year) (Jordan: 14.6 kg BOD/person/year); DOC – Degradable Organic Carbon (fraction of BOD) (0.55 for developing countries (IPCC); DOCf – Fraction of DOC that decomposes (Default: 0.5

(IPCC)); MCF – Methane Correction Factor (Untreated wastewater: 0.8 (anaerobic conditions), Treated wastewater: 0.1–0.3 (depends on technology)); F – Fraction of methane in biogas, 0.60 (IPCC); (16/12) – Molecular weight ratio (CH_4 to carbon); R – Methane recovery (the methane recovery (R) from wastewater is currently negligible (≈0) in most cases, as the country lacks large-scale biogas capture systems for wastewater)

2.4.3 Future Projections

Future methane emissions to 2050 were modeled within LEAP-IBC's dynamic framework, where sectoral pathways are rigorously coupled to Jordan's core socioeconomic indicators—population and GDP growth—through empirically validated response functions in connection with the past trends of data between 2019-2023 ("LEAP: Low Emissions Analysis Platform," n.d.). Here are listed how each sector projected:

A. The agriculture sector's emissions trajectory was directly scaled to projected GDP expansion, capturing its role as an economically sensitive source where intensification of livestock operations and cropland management drives methane generation proportional to broader economic development.
B. Concurrently, population growth served as the primary driver for waste and wastewater sectors, with per-capita generation rates held constant to reflect urbanization trends.
C. While transportation fuel demand followed annual recursive allocation based strictly on demographic shifts using the function: $C_t = C_{t-1} \times P_t/P_{t-1}$, where fuel consumption (C) in year t responds proportionally to population (P) shifts.
D. The energy sector employed a hybrid approach: initial projections were generated through GDP-linked growth elasticities, then refined via secondary calibration to population dynamics, ensuring compound sensitivity to both economic output and demographic pressure.

Across all sectors, LEAP-IBC's integrated GrowthAs algorithm converted these driver relationships into quantitative emission pathways by applying variable-specific growth rates.

2.4.4 Methane Emissions Conversion into CO_2 Equivalent

Methane emissions were converted to CO_2 Equivalent (CO_2eq) using Global Warming Potentials (GWPs), which compare the warming impact of 1 ton of a gas to 1 ton of CO_2 over a set period("Understanding Global Warming Potentials | US EPA," n.d.). The choice of time horizon for calculating impacts involves a trade-off: longer horizons emphasize long-term climate stability, while shorter ones prioritize near-term cooling(IPCC 2014). Given Jordan's policy community's familiarity with GWP100, this metric aligns with its NDCs. from the IPCC Fifth Assessment Report(IPCC 2014), the global warming potential (GWP) of methane over a 100-year time horizon is 28. Methane emissions or reductions can therefore be expressed in terms of CO_2 equivalent (CO_2eq) using the equation:

$$\mathbf{CO_2eq = Methane\ (tons) \times GWP_{100}}.$$

2.5 Development of Methane Mitigation Pathways

The process for developing Jordan's methane mitigation pathways, integrating policy-driven measures with multi-stakeholder represented Jordanian government to ensure actionable and scientifically grounded interventions, commenced with extraction of mitigation measures, projects, and actions from national documents—including Jordan's NDCs (Jordan Government 2021), National Communication Reports (UNDP 2022), National Climate Policy (Ministry of Environment 2022), National Biennial Update Reports(Jordan Government 2014; 2020), and sector-specific strategies from key ministries. Then these measures, actions, and projects are categorized by timeframe (short-term: 2022-2029; mid-term: 2030-2039; long-term: 2040-2050). These measures were later validated through stakeholder workshops with key ministries and municipal authorities including Ministry of Energy & Natural Resources, Ministry of Transport, Land Transport Regulatory Commission, Civil Aviation Regulatory Commission, Ministry of Agriculture, Greater Amman Municipality, Ministry of Local Administration, Ministry of Environment, Ministry of Water & Irrigation, Ministry of Health, Drivers & Motor Vehicles Licensing Department, Ministry of Industry Trade & Supply, Ministry of Planning & International Cooperation, and other inline authorities to assess feasibility and implementation barriers. Finally, four scenarios (Baseline plus three mitigation pathways) were modeled in LEAP-IBC. The resulting framework integrates policy directives, stakeholder consensus, and technical modeling to deliver actionable, evidence-based mitigation pathways for Jordan's key methane-emitting sectors.

2.6. Uncertainty and Limitations

This work employs Jordan's official national data and IPCC-endorsed emission factors, ensuring alignment with global standards while acknowledging inherent uncertainties in all real-world datasets. The LEAP-IBC model provides a robust baseline for policy analysis, with its constant emission factors enabling clear benchmarking while remaining adaptable to technological updates. Stakeholder consultations through FGDs incorporated diverse institutional expertise, ensuring practical feasibility while being cross validated with technical modeling. These approaches reflect best practices in climate policy design, combining authoritative data, proven modeling frameworks, and multi-stakeholder input to deliver actionable and scientifically grounded methane mitigation pathways for Jordan. However, major limitations pertain such as:

3 Results

3.1 National Methane Emissions (2022 Baseline)

Emissions were estimated across four main sectors: Agriculture, Energy, Transportation, and combined Waste/Wastewater. The Waste and Wastewater sectors were analyzed as a single sector because nearly all treatment plants in Jordan dispose its sludge in landfills, meaning these emissions are already included in landfill waste figures. Additionally, wastewater collection and treatment processes generate only minimal methane emissions due to Jordan's advanced wastewater management scheme. This combined approach provides a more accurate representation of actual methane emissions from waste management in Jordan.

Jordan’s total methane emissions for 2022 amounted to about 6,979 Gg CO_2 equivalent per annum (Gg CO_2 eq/a), with the waste/wastewater sector being the dominant source, contributing 70% (4,886 Gg) of emissions. The agriculture sector ranked second, accounting for 18.8% (1,3088 Gg), followed by the energy sector at 10.3% (720 Gg). In contrast, transport (62.6 Gg, 0.9%) and oil refining (1.1 Gg, 0.02%) were minor contributors, each representing less than 1% of the total. These findings underscore the importance of prioritizing mitigation efforts in waste management and agricultural practices to address the majority of Jordan’s methane emissions effectively. Figure 1 highlights sectoral distributions, presents Jordan's sectoral breakdown of methane emissions for 2022.

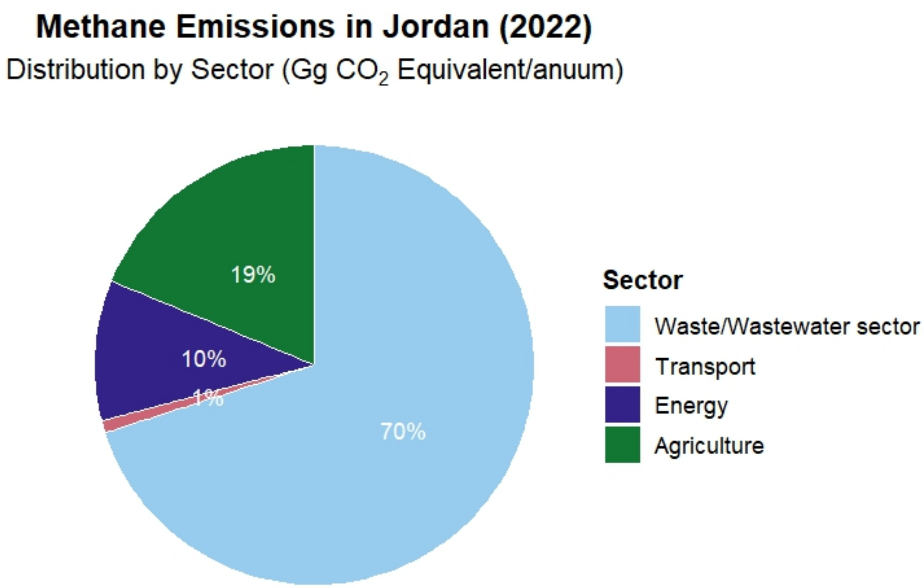

Figure 1: Sectoral Distribution of Methane Emissions in Jordan (2022)

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In 2022, total direct methane emissions from the waste and wastewater sectors in Jordan reached approximately 4,886 Gg CO_2e/a. The majority of these emissions originated from municipal solid waste (MSW) in landfills, which also receive sludge from wastewater treatment plants that contributes 4,317 Gg CO_2e, making it the dominant contributor within the waste sector. In contrast, methane emissions from domestic wastewater management, including sewer networks, treatment units, and small scale discharge into wadis and open bodies, accounted for a smaller yet notable share of 569 Gg CO_2e. These findings underscore the significant impact of landfill management practices on overall methane emissions mitigation in the sector.

The agriculture sector contributes about 1,308 Gg CO_2e/a, primarily through two key processes: enteric fermentation (digestive processes in livestock) and manure management. These emissions are driven by Jordan's livestock populations, including cows (153.72 kt CO_2e), sheep (511 kt CO_2e), goats (636.38 kt CO_2e), camels (6.22 kt CO_2e), and poultry (0.86 kt CO_2e). Among these, goats and sheep collectively account for 88% of the sector's emissions, reflecting their dominant role in Jordan's livestock production.

Jordan's energy sector contributes 720 Gg CO_2 equivalent of methane emissions annually. The primary sources include diesel combustion (247 Gg, 34.2% of sectoral emissions), followed by oil (242 Gg, 33.7%) and natural gas (174 Gg, 24.2%). Coal, while a minor contributor, accounts for 6 Gg (0.9%), with LPG emitting 32 Gg (4.4%). Other fuels—such as kerosene (4 Gg), gasoline (0.03 Gg), and miscellaneous sources (15 Gg)—represent negligible shares (<1% combined). These findings highlight diesel and oil as the dominant drivers of energy-related methane emissions, suggesting that mitigation strategies should prioritize these subsectors for measurable impact.

The road transport sector contributes 62 Gg CO_2 eq/a in Jordan. The vast majority of these methane emissions stem from gasoline-powered internal combustion engines (ICE), accounting for 56 Gg (90.2% of sectoral emissions). Diesel vehicles follow distantly with 5 Gg (8.4%), while jet fuel (0.72 Gg, 1.2%) and fuel oil (0.16 Gg, 0.3%) play minimal roles. These findings reveal that gasoline vehicles are by far the dominant source of methane in Jordan's transport sector, suggesting that emission reduction strategies should prioritize improvements in gasoline engine efficiency and fuel quality standards to achieve meaningful mitigation.

3.2 Projected Methane Emissions: 2022-2050

Methane emissions are expected to rise if current activities remain unchanged in the future. The LEAP model utilized historical trends from the past five years, combined with GDP and population growth projections, to forecast methane emissions for Jordan in 2030, 2040, and 2050. The results, illustrated in figure 2, highlight sector-specific trends in methane emissions over this period. The most significant increases occur in the waste and energy sectors.

Transportation emissions are expected to rise from 62.62 to 112.69 Gg CO_2e/a, with gasoline remaining the dominant contributor. The energy sector could see emissions grow from 720 to 1,366.37 Gg CO_2e/a, primarily from gasoline and diesel. Agricultural emissions, mainly from livestock manure management, may increase from 1,308.66 to 1,585.84 Gg CO_2e/a, with sheep and goats being the largest sources. The waste sector shows the most dramatic growth, with solid waste emissions nearly doubling from 4,317.58 to 7,769.88 Gg CO_2e/a.

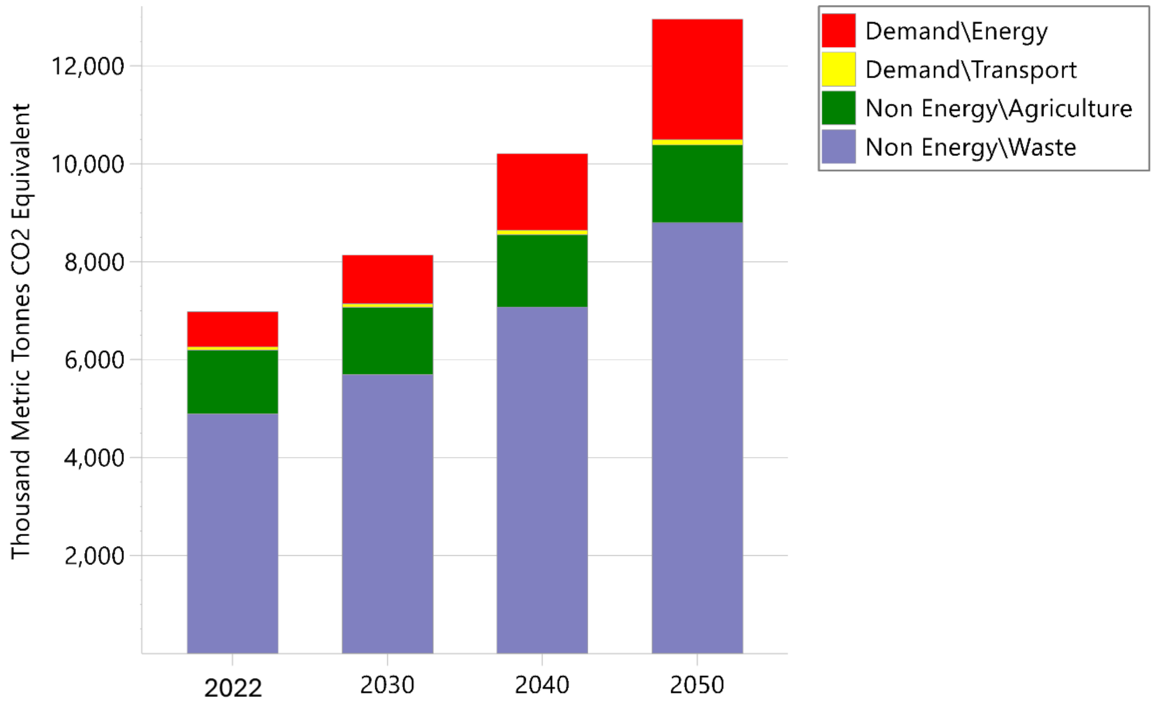

Figure 2: Forecasted Baseline Emissions of Methane from all sectors in Jordan.

3.3 Emission Reduction Potential of the Governmental Measures

Three scenarios reflect cumulative methane reduction potentials across different time horizons were modeled. The short-term scenario shows reductions achievable through immediate measures by 2030. The mid-term scenario combines these short-term reductions with additional benefits from medium-term measures implemented by 2040. The long-term scenario incorporates all previous reductions while adding further gains from long-term measures initiated later by 2050. This analysis assumes all implemented measures will continue operating through 2050, demonstrating how progressively adopting additional mitigation strategies can compound emission reductions over time**.**

Figure 3 shows all scenarios begin at 6,978 Gg CO_2e/a in 2022, with the baseline rising to 8,129 by 2030 while all mitigation scenarios show 39.3% reductions (4,932). By 2040, the baseline reaches 10,202 as the Mid-Term scenario reaches 48.6% reductions (5,246) and Long-Term (6,305, 51.3%) scenario demonstrates progressively stronger impacts. This reveals that while early action delivers immediate reductions, combining sustained interventions yields compounding benefits - through layered mitigation strategies.

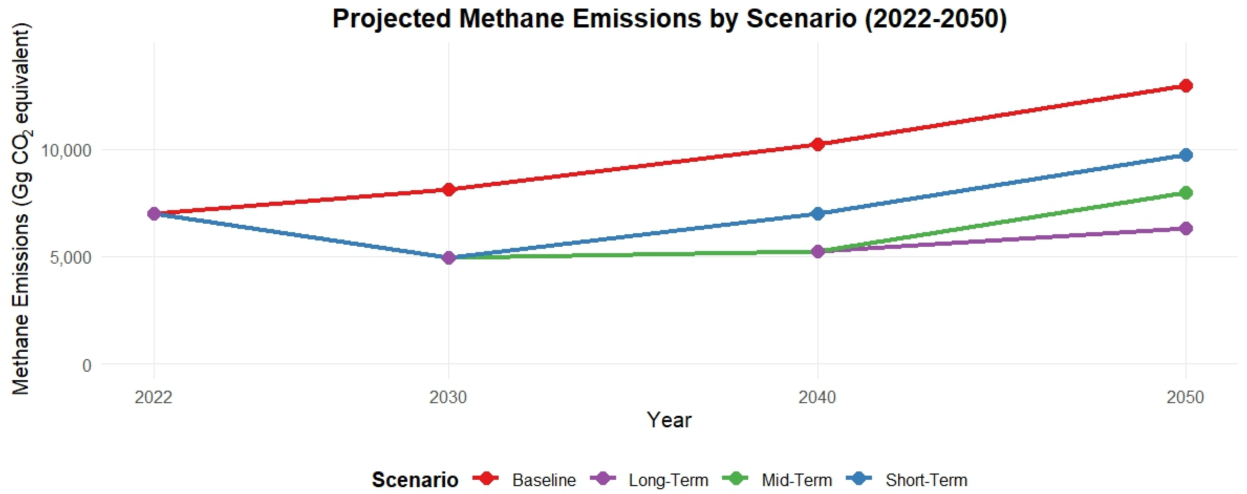

Figure 3: Projected Methane Emissions Trajectories Under Different Mitigation Scenarios (2022-2050)

The Jordanian government strategy to mitigate GHG emissions including methane across key sectors, including agriculture, waste and wastewater, transportation, and energy are structured into short-, mid-, and long-term initiatives or actions, each targeting specific methane emission sources with tailored solutions. Figure 4 illustrates a detailed overview of these efforts and their projected impact within each sector.

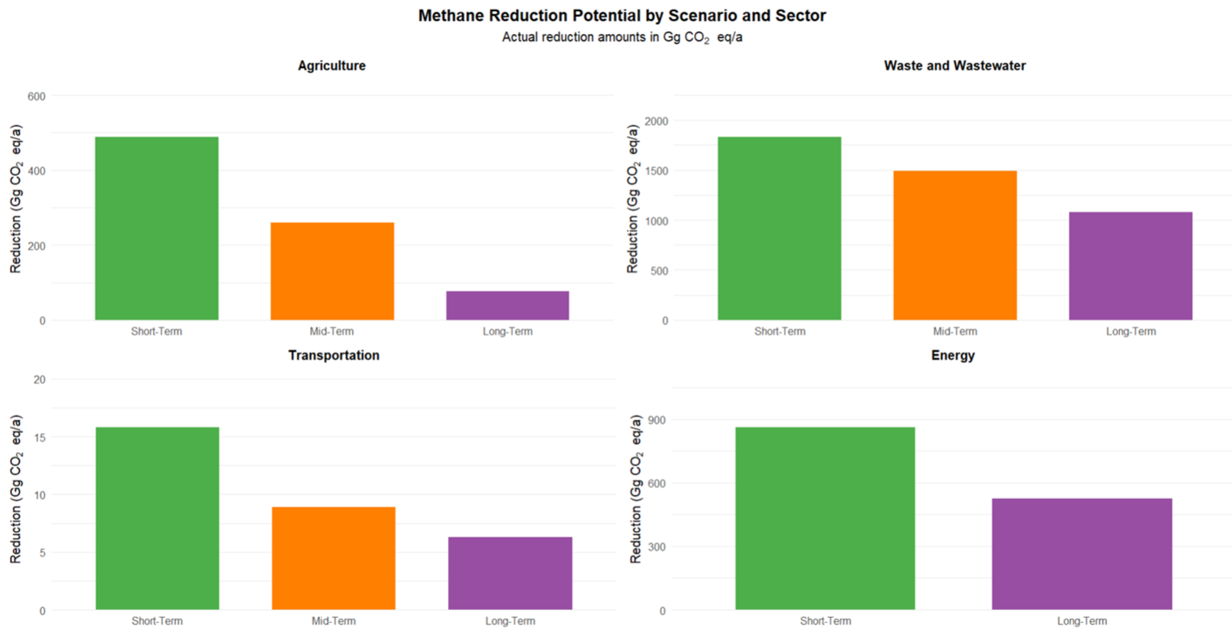

Figure 4: Projected Methane Emission Reductions by Sector and Scenario

3.2.1 Agriculture Sector

As figure 4 represents, the agriculture sector in Jordan is set to implement a series of measures aimed at reducing methane emissions, a potent GHG. In the short term (2024–2030), eleven initiatives will be rolled out, each contributing an estimated reduction of 44.38 Gg CO_2 eq/a. These according to the government plans, include the implementation of agricultural waste management systems, cleaning livestock barns, and distributing Bacillus-based equipment to farmers. Additionally, licensing regulations for livestock barns will be tightened, and awareness campaigns will educate farmers on sustainable practices. Collectively, these short-term actions are expected to reduce emissions by 488.18 GgCO_2 eq/a.

Moving into the mid-term (2031–2040), the focus shifts to circular economy practices and hazardous waste management. Five key actions, such as farm waste recycling systems and biogas units for small farms, will each reduce emissions by 43.29 GgCO_2 eq/a. Empowering women in waste management is another critical initiative under this phase. The total mid-term reduction is projected at 259.74 GgCO_2 equivalent.

For the long term (2041–2050), two high-impact projects will be prioritized: breeding biological bacteria to reduce emissions and implementing thermal sterilization in fertilizer plants. These efforts will yield a combined reduction of 76.72 $GgCO_2$ equ/a. By 2050, the agriculture sector's cumulative mitigation potential is estimated at 779.26 $GgCO_2$ eq/a, demonstrating Jordan's commitment to sustainable agricultural practices.

3.2.2 Solid Waste and Wastewater Sector

The waste and wastewater sector presents significant opportunities for methane reduction, with measures spanning short-, mid-, and long-term horizons. In the short term, seven projects will target landfill gas capture and organic waste processing. Notable among these is the biogas collection initiative at Al-Ekeider landfill, projected to reduce emissions by 754.2 $GgCO_2$ eq/a. The establishment of recycling banks in Amman and organic waste processing plants will further contribute 301.68 $GgCO_2$ equivalent each. These efforts will collectively reduce emissions by 1,829.95 $GgCO_2$ equivalent in the short term.

Mid-term measures include five engineered solutions, such as converting landfills into sanitary facilities, which alone will account for 876.44 $GgCO_2$ equivalent in annual reductions (see figure 4). The development of waste transfer stations and GPS-guided systems for transferring vehicles will enhance efficiency and further curb emissions. The total mid-term reduction is estimated at 1,489.94 $GgCO_2$ equivalent.

Long-term strategies focus on systemic changes, including the utilization of biomass in cement factories, expected to reduce emissions by 862.81 $GgCO_2$ eq/a. Sludge-to-biogas plants will also play a pivotal role. By 2050, the waste and wastewater sector's total reduction potential stands at 4,600.84 $GgCO_2$ equ/a, underscoring its critical role in Jordan's climate strategy.

3.2.4 Energy Sector

The energy sector is a cornerstone of Jordan's GHG mitigation strategy, with governmental measures targeting both short- and long-term reductions. Short-term actions and projects include improving industrial energy efficiency, The rehabilitation of electrical infrastructure and training programs. Clean energy technologies is expected to reduce emissions by **863.24** $GgCO_2$ eq/a.

Figure 4 shows that long-term projects focus on transitioning to renewable energy and alternative fuels. Increasing the share of renewables to 20% by 2050 will reduce emissions by 199.58 $GgCO_2$ eq/a, while the adoption of hydrogen energy and electric vehicles will add significant reductions. The sector's total mitigation potential by 2050 is projected at **1,389.31** $GgCO_2$ equivalent, reflecting Jordan's commitment to a low-carbon energy future.

3.2.3 Transportation Sector

The transportation sector's methane reduction potential follows a phased approach: short-term measures (e.g., Amman Bus Project, Intelligent Transportation Systems) yield 15.83 Gg CO_2eq, mid-term strategies (Bus Rapid Transit expansion, fleet modernization) contribute 8.9 Gg CO_2eq, and long-term projects (low-carbon freight rail) add 6.27 Gg Gg CO_2eq, see figure 4 for more clarification. While the sector's total reduction (31 Gg CO_2eq by 2050) is modest compared to energy, waste, or agriculture, these targeted interventions demonstrate Jordan's commitment to addressing all emission sources.

Transportation's methane reductions are negligible relative to Jordan's three major emitting sectors—where single initiatives often exceed the transport sector's total potential. However, these measures remain strategically valuable, complementing broader decarbonization efforts and setting precedents for integrated climate action in mobility systems.

3 Discussion

The findings of this study underscore the critical role of methane emissions in Jordan's greenhouse gas profile, with the waste and wastewater sector emerging as the dominant contributor, accounting for 70% of total emissions. This aligns with global trends where waste management systems, particularly landfills, are significant methane sources due to anaerobic decomposition of organic matter (Kumar et al. 2024). However, Jordan's situation is exacerbated by rapid urbanization, population growth, and inadequate waste infrastructure, which collectively amplify methane release. The agricultural sector, primarily driven by livestock enteric fermentation and manure management, represents the second-largest source, reflecting Jordan's reliance on agro-pastoral systems. Meanwhile, the energy and transport sectors, though smaller contributors, exhibit growth trajectories tied to fossil fuel dependency, highlighting the need for diversified energy strategies.

The projected rise in methane emissions under a business-as-usual scenario presents a pressing challenge for Jordan's climate goals. Without intervention, emissions could nearly double by 2050, driven by population growth and economic expansion. This trend threatens to undermine Jordan's commitments under the Paris Agreement and exacerbate local environmental and health impacts, such as air pollution and ozone formation. The study's mitigation scenarios, however, demonstrate the potential for significant reductions through targeted policies. Short-term measures, such as landfill gas capture and agricultural waste management, offer immediate benefits, while mid- and long-term strategies, including renewable energy adoption and systemic waste reforms, provide sustained reductions. The layered approach reveals that early action is essential but must be complemented by progressive, long-term planning to achieve compounding benefits.

A key insight from this research is the disproportionate mitigation potential across sectors. The waste sector, despite being the largest emitter, also offers the highest reduction opportunities, particularly through landfill gas recovery and organic waste processing. This suggests that prioritizing waste management infrastructure could yield outsized climate benefits. Similarly, the agricultural sector's mitigation potential, though smaller, is critical given its socio-economic importance. Strategies like improved manure management and biogas systems not only reduce emissions but also align with rural development goals. In contrast, the transport sector's limited impact underscores the need for broader decarbonization beyond methane-specific measures, such as electrification and fuel efficiency standards.

The study's methodology, leveraging the LEAP-IBC model and stakeholder-validated scenarios, provides a robust framework for policy planning. However, uncertainties remain, particularly in emission factors and the implementation feasibility of proposed measures. For instance, the success of landfill gas projects depends on technical capacity and funding, while agricultural interventions require farmer engagement and behavioral change. These challenges highlight the importance of adaptive management and continuous monitoring to refine strategies as new data and technologies emerge.

4 Conclusion

This study fills a critical gap in Jordan's climate policy by offering a comprehensive, sector-specific roadmap for methane mitigation. The findings emphasize the urgency of addressing methane not only for climate objectives but also for co-benefits like improved air quality and public health. By integrating short-, mid-, and long-term measures, Jordan can align its national strategies with global climate targets while fostering sustainable development. Future research should explore the socio-economic impacts of these mitigation pathways and the role of international cooperation in supporting Jordan's transition to a low-emission future.

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Data Availability

The data used in this study are available through the LEAP software model which is delivered to be under the ownership of Jordan Ministry of Environment. A comprehensive profile for Jordan has been established for the baseline year of 2022.

CRediT authorship contribution statement

Alham Al-Shurafat: Conceptualization, Methodology, Formal analysis, Writing - original draft, molding.
Fayez Abdullah: Conceptualization, Methodology, Writing - review & editing.
Ayman Sharafat: Methodology, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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